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Overview of Differential GPS Methods

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ABSTRACT

A local GPS reference receiver (RR) can be used to eliminate common errors in the GPS navigation solution of other nearby receivers. A threefold improvement in remote GPS position accuracy can be achieved by this technique under optimum conditions. Several methods of accomplishing this process are presented.

INTRODUCTION

The NAVSTAR GPS under development by the Department of Defense (DoD) will provide highly accurate position, velocity, and time anywhere in the world to users equipped with suitable GPS receivers. The GPS operates by the use of a constellation of 18 satellites in 12-hour (19,000-km) orbits that continuously broadcast their identification, position, and time using specially coded signals. The typical accuracies quoted for user equipment operating in P code are: positioning to 10 m RMS in each axis; velocity to 0.1 m/s RMS in each axis; and time to 0.1 μs.[1] Although these accuracies are considered exceptional for navigation systems, test and training ranges and other applications can require even more accurate positioning information.

One technique for improving the performance of GPS positioning that is receiving increasing interest is the use of differential GPS processing. This concept involves the use of data from a GPS RR in the vicinity of the GPS receiver-equipped participants that allows certain errors common to both receivers to be removed from the participant's position measurements. Several schemes to accomplish differential GPS have been identified; this paper discusses and contrasts some of these schemes.

GPS Error Sources

The GPS receiver computes its position from the receiver-to-satellite ranges it has determined through signal reception time measurements and from satellite orbital information and time transmitted by the satellite. Each satellite transmits its identity number, the time (resolved to the nearest nanosecond), and orbital ephemeris corrections, in addition to a host of other data (such as health, clock errors, drift rates, etc.). The receiver basically obtains the range to the satellite vehicle (SV) by noting the difference in the time the signal is received (using the receiver's clock) and the transmitted time. Because the receiver's clock error may be large relative to the ranging accuracy required (feet), the receiver's SV ranges are termed pseudoranges (PRs), and four such ranges from separate SVs are used to provide an overdetermined 3-D solution, thus eliminating the receiver's clock error. The location of each SV is obtained using the SV's ephemeris message to allow the receiver to calculate its position, which is defined in terms of earth-centered, earth-fixed coordinates.

Several sources of error are associated with this process, however, and our interest is with those which can be eliminated or significantly reduced because they are common to both participant and reference receivers. Fundamentally, these errors are composed of the satellite's clock error, errors in the satellite's broadcasted ephemeris data, and signal propagation delays that are not accounted for by the receiver's measurements or modeling. These errors will be seen over the relatively short intervals of a test or training operation (about 10 to 20 min) as relatively constant bias errors in the receiver's position data. When two receivers in the same vicinity (within about 100 nmi) are using the same set of four satellites (up to seven or eight can be above the local horizon at one time), the above errors will be common to both and can be removed or essentially eliminated by differential techniques.

Another source of receiver position error is selective availability (SA), which will be imposed by DoD and will limit C/A code users to around 250-m accuracy in the absolute navigation mode.[2] Only authorized users will be able to access P code. Differential GPS, however, will enable civilian sector C/A-code receivers to substantially eliminate SA effects in a local region near a reference receiver as well as remove other common errors. Other error sources in the positioning process that are not correlated between two receivers are: receiver interchannel biases, receiver noise and quantization errors, and local multipath effects.

Table 1 tabulates a typical error budget for nondynamic GPS (absolute mode) user equivalent ranging error (UERE) and subsequent position determination for a nominal carrier to noise ratio (C/N_o) of 38 dB-Hz. The satellite clock error and the control segment ephemeris errors (up-loaded for SV retransmission by the satellite control segment) are common to both P-code and C/A-code operation. The ionospheric delay is determined by dual frequency measurements (L_1 & L_2) for P code, but is estimated by an algorithm when in C/A-code operation

Table 1—GPS Static Error Budget

Error Source	Predicted Error (ft)	
Satellite clock error	10	
Ephemeris error	8.6	
	P code	C/A code
Ionospheric delay error	1.3	21.0
Tropospheric delay error	1.3	1.3
Receiver noise/quantization errors	0.8	8.0
Receiver interchannel bias	0.5	2.0
Multipath	4.0	10.0
UERE (RMS)	13.9	27.9
Resulting Position Accuracy		
RMS horizontal (x,y) position error (assume HDOP = 1.5)	21	42
RMS vertical (z) position error (assume VDOP = 2.5)	35	70

Source: Reference 4

since only L_1 is used and is consequently less precise. The tropospheric delay error is estimated by an algorithm for C/A code and P code and is the same for both. Receiver noise and quantization errors are noncorrelated and are seen to be ten times less for P code than for C/A code because of the 10:1 bandwidth differences between the two codes. Receiver interchannel biases can be considered as those PR differences between multichannel receiver measurements if all four channels were tracking the same satellite. Multipath errors are unique to receiver location and antenna installation and are, therefore, noncorrelated between two receivers.

Differential GPS Error Budgets

Figure 1 illustrates the principle of common error removal by differential GPS. A reference receiver at a known (surveyed) location measures the range to a NAVSTAR satellite. This measured range includes the actual range to the satellite plus several errors. These errors are taken as additive (for illustrative convenience) and include the satellite clock error, the tropospheric delay, and the ionospheric delay. Since the reference receiver's coordinates are known, the satellite's ephemeris message allows the range to be calculated; however, an ephemeris error can exist in the calculated range, so the difference between the measured range and the calculated range includes all previously discussed errors. If this range correction is applied to the measured range of a remote GPS user, a "corrected" range is obtained that will allow the remote receiver to remove the error in its uncorrected position. For clarity, this basic diagram assumes the receiver's clock bias term has been removed from the satellite range measurements and does not show noncommon receiver-unique errors such as receiver noise and quantization errors or local multipath errors.

Considering that two receivers are using the same set of SVs, the satellite clock and ephemeris errors are obviously common to both and to a large degree the ionospheric delays are common due to the high altitude of the ionosphere (25 to 250 nmi).

With increasing separation distance between remote and reference receivers, a slight decorrelation occurs with the ionospheric delays and satellite ephemeris errors due to difference in satellite viewing angles. Ephemeris error decoupling between two receivers has been estimated by Beser and Parkinson[2] for receiver separations of 100 nmi and a worst-case situation where all the ephemeris error is in the along-orbit direction. This error is of the order of 0.5 m for each 100 m of along-orbit ephemeris error. Ionospheric delay decoupling with receiver separation is more difficult to estimate due to diurnal and seasonal variations in the ionosphere. Static differential field test measurements have been reported by Fickas and Wadsworth[3] using Phase I GPS equipment. These data were taken for receiver separations of 0.5 nmi up to 280 nmi. The bulk of these data was obtained at night (when the ionosphere is stable), although some day-night transition measurements were included. Dispersions (i.e., spread) in the horizontal and vertical RMS data (approximately ± 1 m in horizontal P-code data, and ± 3 m in the vertical data) were masking any trends of error growth over the 280-nmi separation, although an error growth of ~ 1 m could have been easily embedded in the data. Thus, it may not be unreasonable to consider employing differential GPS for up to 300-nmi separations.

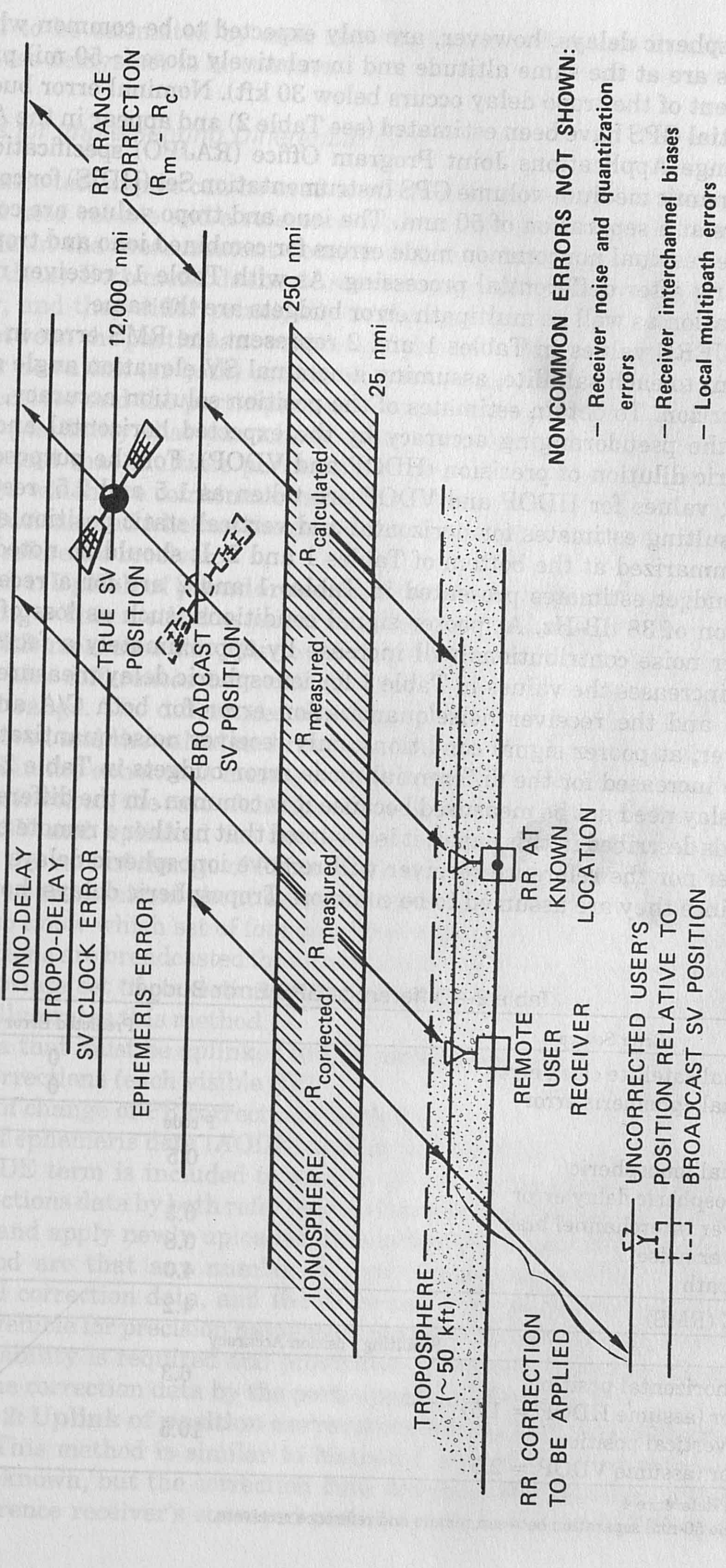

Fig. 1—Basic diagram for common error removal by differential GPS

Tropospheric delays, however, are only expected to be common when both receivers are at the same altitude and in relatively close (~50 mi) proximity (90 percent of the tropo delay occurs below 30 kft). Nominal error budgets for differential GPS have been estimated (see Table 2) and appear in the Air Force GPS Range Applications Joint Program Office (RAJPO) specification[4] for a high-dynamic medium-volume GPS Instrumentation Set (HDIS) for co-altitude receivers at a separation of 50 nmi. The iono and tropo values are considered to be the residual noncommon mode errors for combined iono and tropo delays remaining after defferential processing. As with Table 1, receiver noise and quantization as well as multipath error budgets are the same.

The UERE values in Tables 1 and 2 represent the RMS error in PR measurement to each satellite, assuming a nominal SV elevation angle about the local horizon. To obtain estimates of the position solution accuracy, one multiplies the pseudoranging accuracy by the expected horizontal and vertical geometric dilution of precision (HDOP and VDOP). For the purposes of estimation, values for HDOP and VDOP are taken as 1.5 and 2.5, respectively. The resulting estimates for horizontal and vertical static position accuracies are summarized at the bottom of Tables 1 and 2. It should be noted that the error budget estimates presented in Tables 1 and 2 are for a receiver C/N_0 condition of 38 dB-Hz. At poorer signal conditions (such as loss of lock) the receiver noise contributions will increase by approximately a factor of four, which increases the values in Table 1 for ionospheric delay measurements for P code and the receiver noise/quantization error for both C/A and P code. However, at poorer signal conditions, only receiver noise/quantization errors will be increased for the differential mode error budgets in Table 2, since the iono delay need not be measured because it is common. In the differential GPS methods described in this paper, it is assumed that neither a remote participant receiver nor the reference receiver will remove ionospheric delays from their data since they are assumed to be common. Tropospheric delays, however, are

Table 2—Differential GPS Error Budget*

Error Source	Predicted Error (ft)	
Residual satellite clock error	0	
Residual ephemeris error	0	
	P code	C/A code
Residual ionospheric/ tropospheric delay error	0.5	0.5
Receiver interchannel bias	0.5	2.0
Receiver noise	0.8	8.0
Multipath	4.0	10.0
UERE (RMS)	4.2	13.0
Resulting Position Accuracy		
RMS horizontal position error (assume HDOP = 1.5)	6.3	19.5
RMS vertical position error (assume VDOP = 2.5)	10.5	32.5

Source: Reference 4

*Assume 50-nmi separation between remote and reference receivers.

assumed to be estimated by each receiver, since differences in altitude can cause these delays not to be common.

Methods for Implementing Differential GPS

Two basic techniques can be used to effect differential GPS between a GPS-equipped user vehicle and a reference receiver; corrections can be determined and made in the measurement domain (PR data) or in the solution domain (position data). Both methods should result in essentially the same final position accuracy, and they differ principally in the specific data that must be transferred between the participant vehicle and the reference receiver, and whether uplink or downlink (or both) communication paths are used between the reference receiver and the participant vehicles. All schemes discussed accommodate the possibility that participants may independently select sets of four satellites and that multiple participants can be involved. Four methods are considered which are combinations of either corrections of PRs or of the navigation solutions, and whether the corrections are made on board the participant or at the reference receiver.

Method 1: Uplink of pseudorange corrections for participant on-board processing—This method requires that the position of the RR is known and that the RR measures the PRs to all visible satellites (typically seven) and computes the differences between the calculated range to the SV and the measured range. The differences are taken after the receiver clock bias has been removed and the calculated range to each SV uses the satellite's position as defined in the ephemeris message. Because the satellites are in motion and SA may be invoked, the rate of change of PR corrections should also be computed for each SV and uplinked for use by the participants. Another reason for including the rate of change of PR corrections is that uplinked correction data need only be transmitted about every six seconds. In this method, the RR does not need to know which set of four satellites a given participant is using since PR corrections are broadcasted for all visible SVs. Each participant thus selects the appropriate set of corrections and applies them to its position processing. Figure 2 illustrates this method.

The data that must be uplinked in this method include:

- PR corrections (each visible SV)
- Rate of change of PR corrections (each SV)
- Age of ephemeris data (AODE) used by RR (each SV).

The AODE term is included to assure the use of the same ephemeris and clock corrections data by both reference and remote receivers, since one receiver may read and apply newly uploaded data before the other. The advantages of this method are that any number of participants can receive and use the differential correction data, and the corrected position data are available on board the vehicle for precision navigation purposes. Disadvantages are that an uplink capability is required and provisions are needed for on-board incorporation of the correction data by the participant's GPS receiver.

Method 2: Uplink of position corrections for participant onboard processing—This method is similar to Method 1 in that the reference receiver position is known, but the correction data are computed based on differences in the reference receiver's surveyed position coordinates and GPS measured

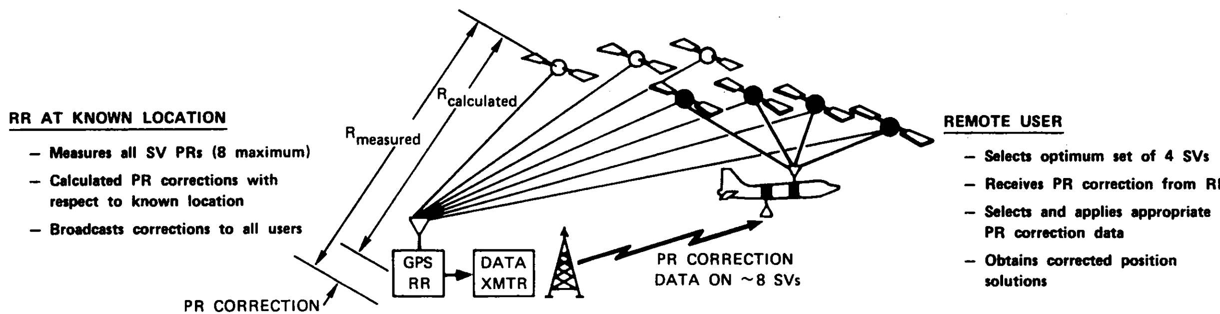

Fig. 2—Differential GPS—Method 1

coordinates. Conceptually, these coordinate errors (ΔX, ΔY, ΔZ) can be uplinked to a participant for correcing its navigation solution. Of course, the position corrections must be derived for the same set of satellites the participant is using. Method 2 is illustrated in Figure 3. For Method 2, the uplinked data will include:

- ΔX, ΔY, ΔZ corrections for each user's SV set
- Rate of change of the corrections ($\Delta\dot{X}$, $\Delta\dot{Y}$, $\Delta\dot{Z}$)
- AODE (each SV)
- Participant's address.

The advantage of this method (as with Method 1) is that the corrected position data are available at the participant vehicle. Disadvantages of Method 2, however, outweigh its advantage. First, it obviously requires an uplink capability as well as correction processing provisions at the participant. Second, the participant may need to downlink its selected set of 4 SVs. More importantly, when multiple participants are involved (and it is impractical to require that all participants use the identical set of four SVs because of vehicle structural masking of the antenna), up to 70 combinations of four satellites are possible when eight are above the horizon. Thus, the designer must require that either (1) all participants use the same set of four SVs, (2) each participant downlinks the set of four SVs it uses so the RR produces the appropriate correction terms for each user, or (3) the RR ground system broadcasts corrections for all possible SV combinations.

Method 3: Downlink all participants' raw-measured data for ground differential processing—This method involves differential corrections in the measurement domain, differing from Methods 1 and 2 in that the differential processing is performed at the reference receiver's location. This method was conceived to take advantage of a ground computer's larger capacity to perform more sophisticated processing than is typically possible in a remote participant's navigation processor. Also, this method is applicable when no uplink is available and when corrected position data are not required on board the participant vehicle. The data to be downlinked for this method include inertial sensor data, which are usually required on board high-dynamic vehicles to preserve accuracy and to accommodate position data integrity during satellite obscuration during maneuvers. Figure 4 illustrates Method 3. The data that must be downlinked from each participant are:

- Four PRs and PR rates
- Four satellite ID numbers
- AODE (each SV)
- Receiver ID
- User time
- Measurement quality estimates
- IRU attitude tests (3)
- IRU accelerations (3)
- Attitude estimate (direction cosines)
- Accurate time-tags for all measured data.

The reference receiver produces the same PR corrections for all visible satellites, as in Method 1. These data are made available to the ground-based position processing system along with the downlinked data from each participant.

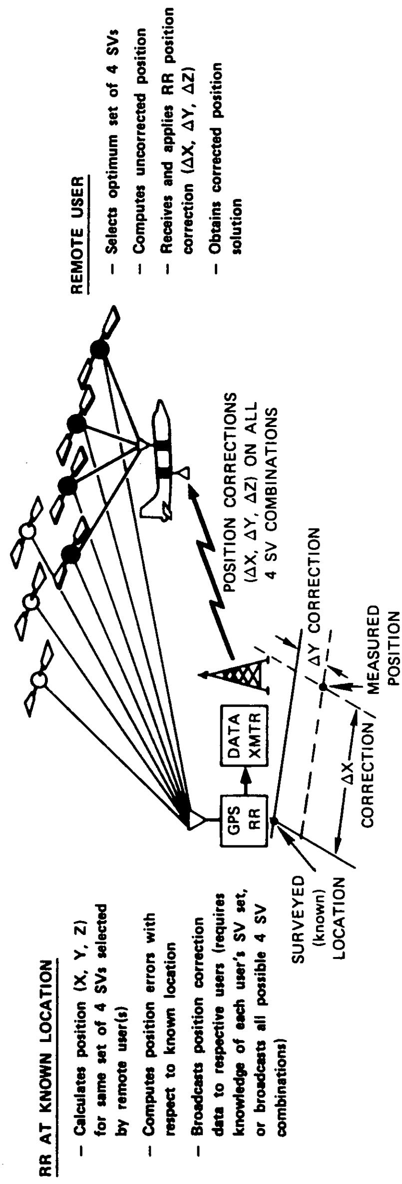

Fig. 3—Differential GPS—Method 2

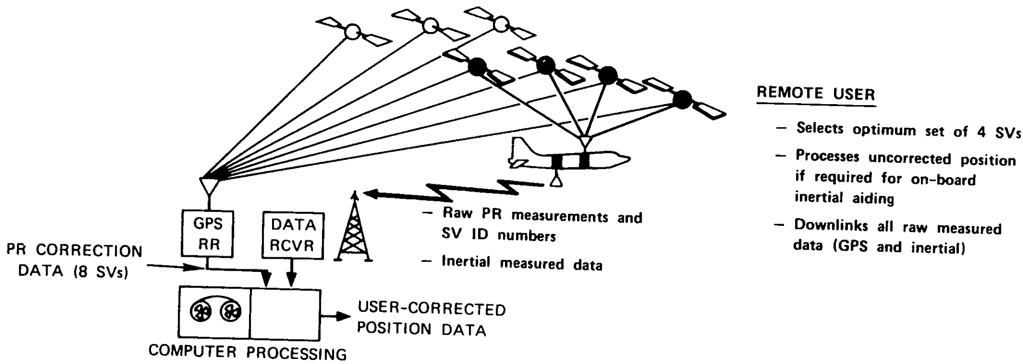

Fig. 4—Differential GPS—Method 3

Advantages of Method 3 are as noted earlier; no uplink is required and more extensive ground data processing resources can be used for the differential navigation solution. Disadvantages are seen in the large amount of raw data to be downlinked for ground-based differential processing. Additionally, if the user requires the corrected data on board, then an uplink would also be required.

Method 4: Downlink uncorrected participant position data for ground differential processing—This method performs differential corrections in the solution domain and can also be used with or without the position of the RR being known. Method 4 is used (1) for applications that do not require the corrected position data to be on board the remote user platform, (2) where an uplink and on-board differential processing are not available, and (3) when large amounts of raw measurement data are not easily downlinked. Method 4 requires each participant to downlink its uncorrected position data along with the satellite set being used. The RR (when it's position is known) can calculate the (ΔX, ΔY, ΔZ) corrections (using the same set of satellites as the participant). These corrections are then applied to the respective participant's (X, Y, Z) position data to obtain the differentially corrected position data. Of course, a separate set of reference receiver (ΔX, ΔY, ΔZ) corrections must be made for each unique participant set of four satellites. Rather than having a large number of separate navigation processors working with the reference receiver's eight sets of satellite measurements, it has been suggested that the set of eight PR corrections can be used with a simple matrix inverter to derive each set of four (ΔX, ΔY, ΔZ) corrections to correspond with each participant's choice of satellites. Method 4 is illustrated in Figure 5.

When the RR position is not accurately known (e.g., with an at-sea application), one may use Method 4 by downlinking uncorrected participant positions (including SV numbers) and simply difference these data from the RR's measured position as determined by using the participant's set of satellites in separate navigation processors for each satellite set. This process has been termed *relative* GPS because the processed participant's location is not tied to absolute position on the earth, but is relative to the reference receiver, which may be taken as the origin of a local tangent plane. The data that must be downlinked from each participant are:

- Uncorrected participant position (X, Y, Z)

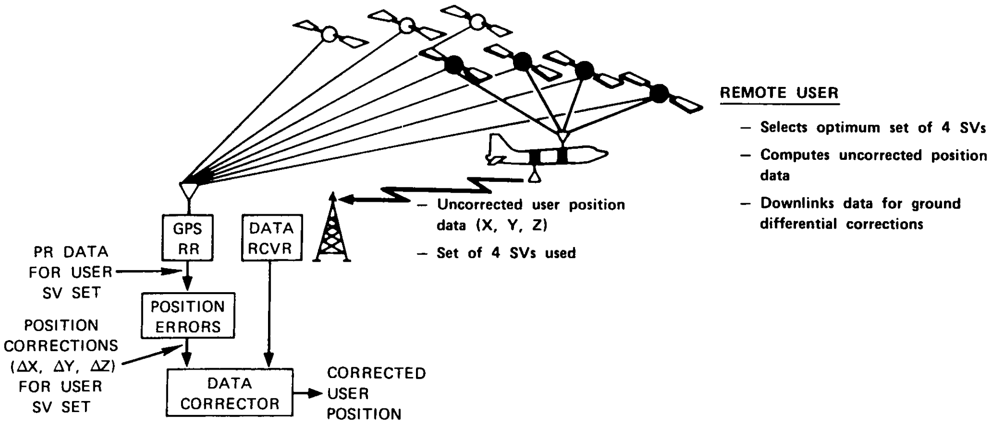

Fig. 5—Differential GPS—Method 4

- Satellite (vehicle) ID numbers
- Data measurement time
- AODE (each SV).

Summary and Conclusions

Of the four differential methods discussed, Method 1 (broadcasting PR corrections) and Method 2 (uplinking position corrections) will provide corrected position data on board the remote user's vehicle. This is basic to any application where precise vehicle navigation is required. Method 1 is the preferred method when large numbers of user vehicles must be accomodated, since the PR correction data for ~8 satellites is sufficient regardless of the SV set chosen by a given user. Method 2 is least preferred when multiple users that may use different satellite sets are involved.

Methods that involve strictly ground processing of downlink user vehicle GPS data (Methods 3 and 4) are most applicable to situations where precise position data are required at a central RR facility (e.g., test range target control applications or post-flight processing to obtain higher trajectory accuracies). Method 3 (downlink of all new PRs and inertial data if aiding is used for high-dynamic players) will be the most demanding to implement due to the need for high data-link integrity (to preserve the ground navigation processing filter continuity) and the need for multiple ground processors when multiple objects are involved. Method 4, although reducing the downlink data load requirements, will still require separate differential solution processors when multiple objects are using different satellite sets.

The advantage of differential GPS for DoD authorized receivers can yield up to a threefold accuracy improvement over absolute navigation modes. For the civilian community using C/A code receivers, the advantage is even more dramatic in that up to tenfold accuracy improvements are possible in local regions when selective availability is involved.

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